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SCALE AND TURBULENCE EFFECTS ON THE LIFT AND DRAG CHARACTERISTICS OF THE NACA 65_3-418, a = 1.0 AIRFOIL SECTION

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ADVANCE CONFIDENTIAL REPORT

SCALE AND TURBULENCE EFFECTS ON THE LIFT AND DRAG CHARACTERISTICS OF THE NACA 65_3-418, a = 1.0 AIRFOIL SECTION

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SUMMARY

An investigation in two NACA wind tunnels has determined the effect of Reynolds number and stream turbulence on the lift and drag characteristics of a low-drag airfoil, the NACA 65_3-418, a = 1.0 section, particularly at low Reynolds numbers, to give an indication of the performance of low-drag wings in low-scale tests. The results are correlated with similar data for the same airfoil section in the NACA two-dimensional low-turbulence pressure tunnel to provide data over a range of Reynolds number from 0.19 to 9.0×10^6.

Large increases in minimum drag coefficient were found as the Reynolds number decreased. This effect was particularly marked at Reynolds numbers below 1.5×10^6. At Reynolds numbers below 1.5×10^6, stream turbulence had little effect on the drag characteristics of the NACA 65_3-418 airfoil section when compared on the basis of test Reynolds number but, at higher Reynolds numbers, stream turbulence had a detrimental effect on drag.

Large decreases in maximum lift coefficient were found with decreasing Reynolds number; most of this decrease was encountered at Reynolds numbers above 2.0×10^6. Marked differences in maximum lift were apparent between the results obtained at high and low turbulence. When compared on the basis of effective Reynolds number, however, fair agreement was reached between the data obtained under both turbulence conditions.

Considerable variation of lift-curve slope with Reynolds number was found. Results at low and high turbulence differed as much as 6 percent but yielded the same value of lift-curve slope at a Reynolds number of approximately 4.0×10^6. At Reynolds numbers higher than 4.0×10^6, no scale effect on the lift-curve slope was observed over the range tested.

In view of the large variations in the lift and drag characteristics found for the NACA 65_3-418 airfoil section over a range of Reynolds number from 0.19 to 9.0×10^6, it is thought that the use of low Reynolds number test data relating to low-drag airfoils is unreliable either to estimate full-scale characteristics or to determine the relative merits of airfoil sections at higher Reynolds numbers.

INTRODUCTION

Investigations of scale effect on the lift and drag characteristics of low-drag airfoil sections have regularly been made at Reynolds numbers above 3.0×10^6 and at low stream turbulence in the NACA two-dimensional low-turbulence pressure tunnel (designated TDT). It is well known that other investigations of low-drag-airfoil characteristics are carried out in tunnels with higher turbulence levels at lower Reynolds numbers than the investigations in the TDT. Proper interpretation of these data obtained at low Reynolds numbers and at various degrees of stream turbulence is difficult because of the unknown stream turbulence effect and scale effect at low Reynolds numbers on the characteristics of low-drag airfoils. Extrapolation of these data to higher Reynolds numbers and low turbulence (flight conditions) is unreliable for this reason.

The purpose of the present investigation was to determine the effect of Reynolds number and stream turbulence on the lift and drag characteristics of a low-drag airfoil section through a range of Reynolds number below 3.0×10^6. Models of the NACA 65_3-418, a = 1.0 airfoil section having chords of 6 and 24 inches were tested in the NACA two-dimensional low-turbulence tunnel (designated LTT), which has a stream turbulence of only a few hundredths of 1 percent. This turbulence is considerably below the level at which any change would be noticeable in the critical Reynolds number of a sphere. The tests covered a range of Reynolds number from 2.77 to 0.23×10^6. Models of the same section having chords of 12 and 48 inches were tested in the LMAL 7- by 10-foot tunnel (designated 7 by 10 tunnel), which has a turbulence factor of 1.6 as determined from sphere tests. The test Reynolds numbers ranged from 2.99 to 0.19×10^6.

MODELS AND METHODS

Ordinates for the NACA 65_3-418, a = 1.0 airfoil section are presented in table I. The models having chords of 12, 24, and 48 inches were of wooden construction and were prepared for testing by the methods described in reference 1. The 6-inch-chord model was built of solid aluminum alloy and was polished by hand to give an aerodynamically smooth surface.

The 24-inch-chord model was tested at tunnel pressures of 2, 3, and 4 atmospheres in the TDT at Reynolds numbers of 2.77, 3.1, 6.1, and 9.0×10^6. The same model was tested at atmospheric pressure in the LTT at Reynolds numbers from 0.68 to 2.77×10^6. The 6-inch-chord model was similarly tested in the LTT for a range of Reynolds number from 0.23 to 0.66×10^6 and in the TDT for a range from 0.38 to 4.0×10^6.

In the TDT and LTT, drag was measured by the wake-survey method and lift was obtained by integrating the pressures along the floor and ceiling of the tunnel test section. Because the TDT and LTT have test sections of the same size, the tunnel-wall corrections to lift and drag for each model were the same in both tunnels. The tunnel-wall corrections for the 6-inch-chord model were obtained from the same basic considerations that were used to determine the corrections for the 24-inch-chord model.

In the 7 by 10 tunnel, the models spanned the test section except for a small clearance at each end. They were rigidly attached to the balance frame by torque tubes extending through the tunnel walls. This installation is thought to approximate closely two-dimensional flow and therefore to make it possible to obtain section characteristics.

In the 7 by 10 tunnel, lift characteristics were obtained from force measurements on the tunnel balance system. Drag characteristics were obtained by the wake-survey method. Lift coefficients have been corrected for effects of tunnel-wall interference by using the experimental correction explained in reference 2. The drag coefficients were corrected for tunnel-wall interference by using the same considerations from which the corrections were obtained for the TDT and LTT data.

RESULTS AND DISCUSSION

A comparison of lift data obtained in the LTT and TDT at a Reynolds number R of 2.77×10^6 is presented in figure 1. The LTT data were obtained at atmospheric pressure and a Mach number of 0.194, whereas the TDT data were obtained at a tunnel pressure of $1\frac{2}{3}$ atmospheres and a Mach number of 0.150. The curves are in good agreement both in respect to slope and maximum lift coefficient; it is therefore improbable that any Mach number effect on maximum lift coefficient, which might have been expected from the results presented in reference 3, exists in the LTT data at this Reynolds number.

Lift data from the LTT and TDT are presented in figures 2 to 4 and from the 7 by 10 tunnel, in figure 5. It may be noted in figure 4 that tests of the 6-inch-chord and 24-inch-chord models in the LTT at Reynolds numbers of 0.66 and 0.68×10^6, respectively, are in good agreement.

At values of the lift coefficient above 0.9, a jog in the lift curve (figs. 2 to 4) is encountered. This jog is due to a region of laminar separation on the upper surface just downstream of the leading edge. The jog becomes more marked as the Reynolds number decreases and, at the lowest Reynolds number, the jog in effect determines maximum lift. It may be seen in figure 5 that no jog in the lift curve is found in the results from the 7 by 10 tunnel.

The absence of the jog in these curves indicates that, at the point on the airfoil where laminar separation occurs in the LTT, the flow is already turbulent in the 7 by 10 tunnel because of the high turbulence level. A detailed investigation of this separation effect is reported in reference 4.

Drag data are presented in figures 6 and 7. It may be noted in figure 6 that the extent of the low-drag range increases progressively as the Reynolds number is decreased. The high values of the drag coefficients at low Reynolds numbers appear to be connected with a region of laminar separation just downstream of the point of minimum pressure. Little is known of the laws governing the extent and quantitative effect of this local region of separated flow except that both the extent of the region and the drag increase as the Reynolds number is decreased.

It may be noted in figure 7 that, for the higher test Reynolds numbers, minimum drag occurs in the 7 by 10 tunnel at a lift coefficient of about 0.55 instead of at the design lift coefficient of 0.4. Because of the difficulty of measuring drag by the wake-survey method in the 7 by 10 tunnel, drag data were obtained for only a limited range of lift coefficient.

Curves that show the scale effect on maximum lift coefficient are presented in figure 8. The test results from the 7 by 10 tunnel are plotted against both test and effective Reynolds number. (Effective Reynolds number = Test Reynolds number × Turbulence factor.) The LTT and TDT results are plotted against the test Reynolds number which, of course, would be equal to the effective Reynolds number since the stream turbulence is only a few hundredths of 1 percent. Large decreases in maximum lift coefficient are apparent with decreasing Reynolds number, particularly above an effective Reynolds number of 2.0×10^6. Figure 8 indicates that, below a Reynolds number of 10^6, the data from the 7 by 10 tunnel are in fair agreement with the data from the TDT and LTT when plotted against test Reynolds number. Above a Reynolds number of 10^6, the data from the 7 by 10 tunnel are in good agreement with the data from the TDT and LTT when plotted against effective Reynolds number. It is seen that the rate of increase in maximum lift coefficient is greatest at a Reynolds number of approximately 3.0×10^6. For other low-drag airfoils, neither the value of the Reynolds number at which this rapid increase takes place nor its quantitative effect is known. It is therefore thought that extrapolation of low-scale data or data which do not determine this characteristic should be avoided.

Various curves of drag coefficient against Reynolds number are presented in figure 9. The results obtained for the NACA 65_3-418 section in the LTT and TDT show that for this airfoil the drag does not follow the law for the variation of either laminar or turbulent skin friction over a flat plate. Minimum drag coefficient increases progressively as Reynolds number decreases; this effect is particularly marked at Reynolds numbers below 1.5×10^6.

At Reynolds numbers below 1.5×10^6, LTT and TDT results are in fair agreement with results from the 7 by 10 tunnel when compared on the basis of test Reynolds number. At a Reynolds number of about 1.5×10^6, at which local separation effects are decreasing and reasonably low drag is found on the NACA 65_3-418 section in the LTT and TDT, the results from the 7 by 10 tunnel as plotted against test Reynolds number are starting to diverge from the LTT and TDT results. As the Reynolds number increases, the high turbulence level of the 7 by 10 tunnel moves the transition point toward the leading edge and increases the drag over the values obtained in streams of low turbulence.

A curve of drag coefficient at the design lift coefficient for the NACA 0012 airfoil section is presented in figure 9 for comparison. This curve represents the average of several test results in the LTT. It may be noted that, at Reynolds numbers below 1.5×10^6, the low-drag section no longer shows a lower drag than the conventional section.

Scale effect on lift-curve slope and on the angle of zero lift is shown in figure 10. Data obtained in the LTT at Reynolds numbers of 0.96 and 1.57×10^6 are not presented since sufficient data were not taken to define the slope accurately. Although the scale effect on the angle of zero lift is small, considerable variation of lift-curve slope with Reynolds number is found. In the Reynolds number range from 0.20 to 3.0×10^6, there is at first a divergence and then a convergence of the data obtained under the two turbulence conditions; the maximum difference between the two curves is approximately 6 percent at Reynolds numbers of approximately 10^6. At Reynolds numbers above 4.0×10^6, the slopes appear to be the same under the different turbulence conditions, and there seems to be no further scale effect for the range tested. At a Reynolds number of approximately 10^6, it may be observed that the variation of lift-curve slope with Reynolds number becomes small under the high-turbulence condition. It seems reasonable to expect, however, that the Reynolds number above which the changes in lift-curve slope become unimportant depends considerably on the particular airfoil section and turbulence characteristics of the air stream. The data presented in figure 10 further emphasize the unreliability of using data at low Reynolds numbers to predict full-scale characteristics.

CONCLUDING REMARKS

Large increases in minimum drag coefficient were found as the Reynolds number decreased; this effect was particularly marked at Reynolds numbers below 1.5×10^6. At Reynolds numbers below 1.5×10^6, stream turbulence had little effect on the drag characteristics of the NACA 65_3-418, a = 1.0 airfoil section when compared on the basis of test Reynolds number but, at higher Reynolds numbers, stream turbulence had a detrimental effect on drag.

Large decreases in maximum lift coefficient were found with decreasing Reynolds number; most of this decrease was encountered at Reynolds numbers above 2.0×10^6. Marked differences in maximum lift were apparent between the results obtained at high and low turbulence. When compared on the basis of effective Reynolds number, however, fair agreement was reached between the data obtained under both turbulence conditions.

Considerable variation of lift-curve slope with Reynolds number was found. Results at low and high turbulence differed by as much as 6 percent but yielded the same value of lift-curve slope at a Reynolds number of approximately 4.0×10^6. At Reynolds numbers higher than 4.0×10^6, no scale effect on the lift-curve slope was observed over the range tested.

In view of the large variation in the lift and drag characteristics found for the NACA 65_3-418 airfoil section over a range of Reynolds number from 0.19 to 9.0×10^6, it is felt that the use of low Reynolds number test data relating to low-drag airfoils is unreliable either to estimate full-scale characteristics or to determine the relative merits of airfoil sections at higher Reynolds numbers.

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1. Jacobs, Eastman N., Abbott, Ira H., and Davidson, Milton: Preliminary Low-Drag-Airfoil and Flap Data from Tests at Large Reynolds Numbers and Low Turbulence, and Supplement. NACA ACR, March 1942.

2. Wenzinger, Carl J., and Harris, Thomas A.: Wind-Tunnel Investigation of an N.A.C.A. 23012 Airfoil with Various Arrangements of Slotted Flaps. NACA Rep. No. 664, 1939.

3. Stack, John, Fedziuk, Henry A., and Cleary, Harold E.: Preliminary Investigation of the Effect of Compressibility on the Maximum Lift Coefficient. NACA ACR, Feb. 1943.

4. von Doenhoff, Albert E., and Tetervin, Neil: Investigation of the Variation of Lift Coefficient with Reynolds Number at a Moderate Angle of Attack on a Low-Drag Airfoil. NACA CB, Nov. 1942.

TABLE I

ORDINATES FOR THE NACA 65_3-418, a = 1.0 AIRFOIL SECTION

[All stations and ordinates given in percent chord]

Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
.278	1.418	.722	-1.218
.503	1.729	.997	-1.449
.973	2.209	1.527	-1.781
2.181	3.104	2.819	-2.560
4.639	4.481	5.361	-3.217
7.123	5.566	7.877	-3.870
9.619	6.478	10.381	-4.410
14.636	7.942	15.364	-5.250
19.671	9.061	20.329	-5.877
24.716	9.914	25.284	-6.334
29.768	10.536	30.232	-6.643
34.825	10.944	35.175	-6.824
39.884	11.140	40.116	-6.856
44.943	11.091	45.057	-6.711
50.000	10.774	50.000	-6.362
55.051	10.198	54.949	-5.818
60.094	9.408	59.906	-5.124
65.126	8.454	64.874	-4.334
70.146	7.368	69.854	-3.480
75.154	6.183	74.846	-2.603
80.147	4.927	79.853	-1.743
85.127	3.638	84.873	-.946
90.092	2.350	89.908	-.282
95.046	1.120	94.954	.144
100.000	0	100.000	0

L.E. radius: 1.96. Slope of radius through end of chord: 0.168.

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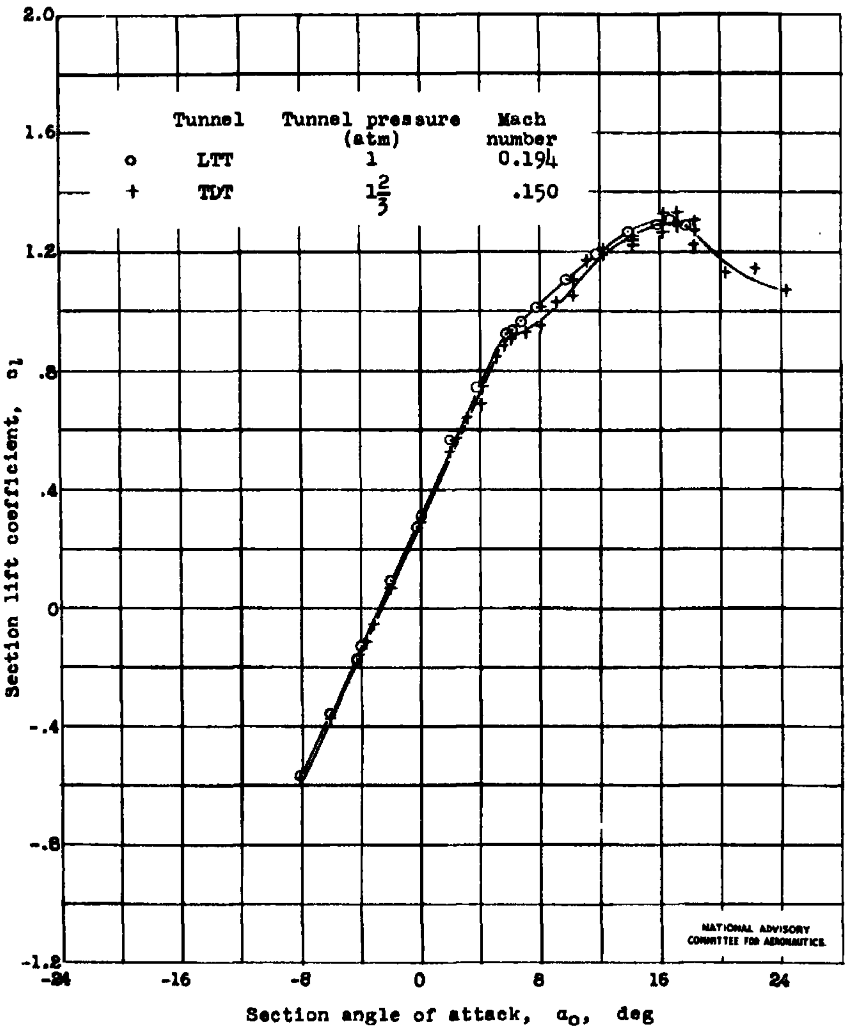
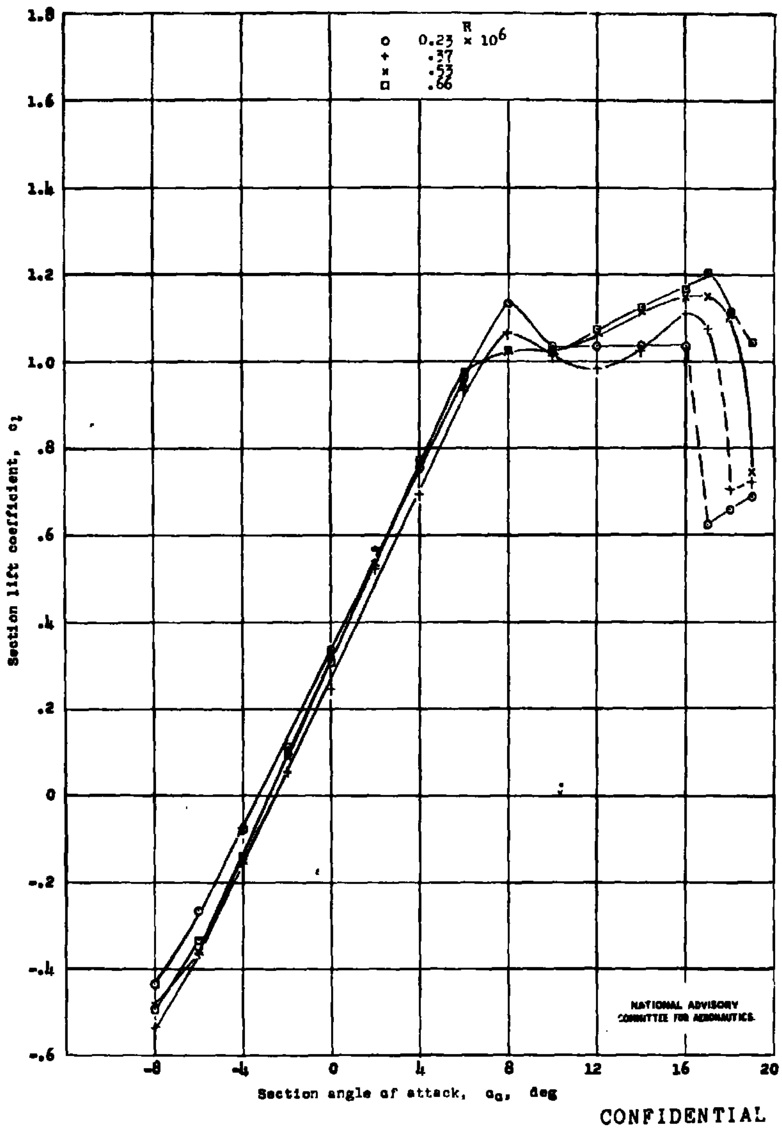


Figure 1 .- Lift characteristics of 24-inch-chord model of NACA 65_3-418, a = 1.0 airfoil section in NACA two-dimensional low-turbulence tunnel (designated LTT) and NACA two-dimensional low-turbulence pressure tunnel (designated TDT). $R = 2.77 \times 10^6$.



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(a) Model having 6-inch chord in LTT.
Figure 2.- Lift characteristics of the NACA 65_3-418 airfoil section.

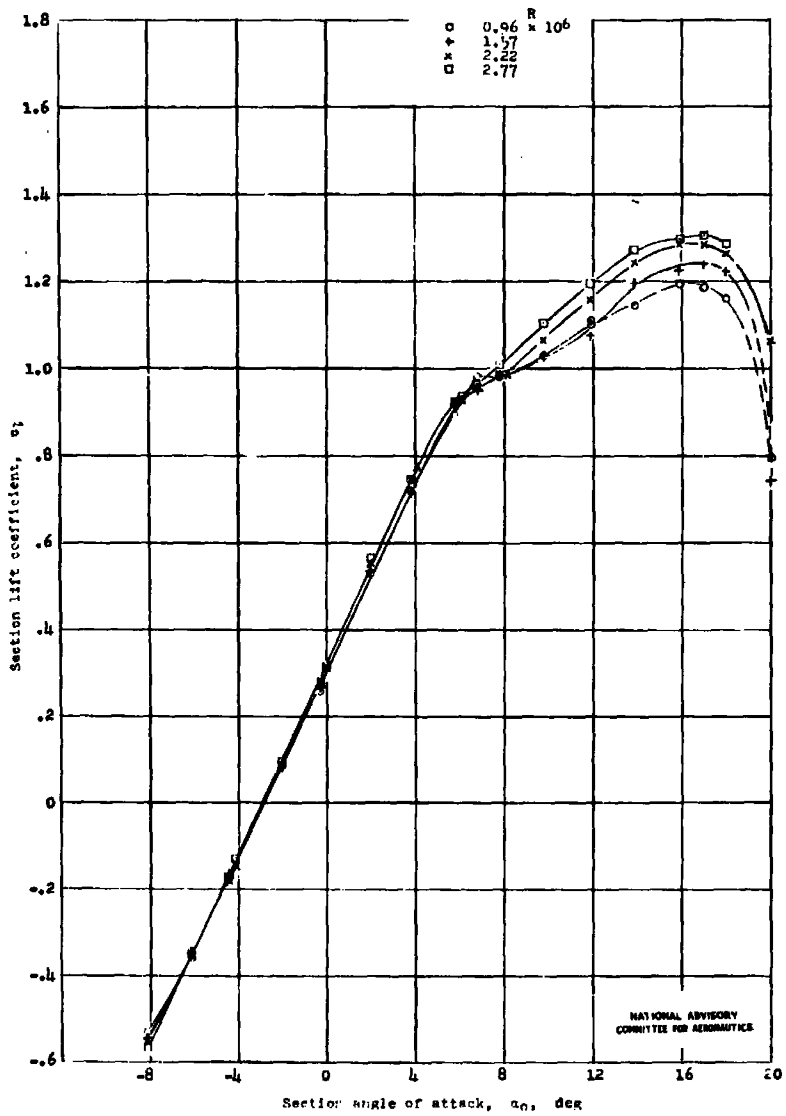

Figure 2.- (b) Model having 24-inch chord in LTT. Continued.

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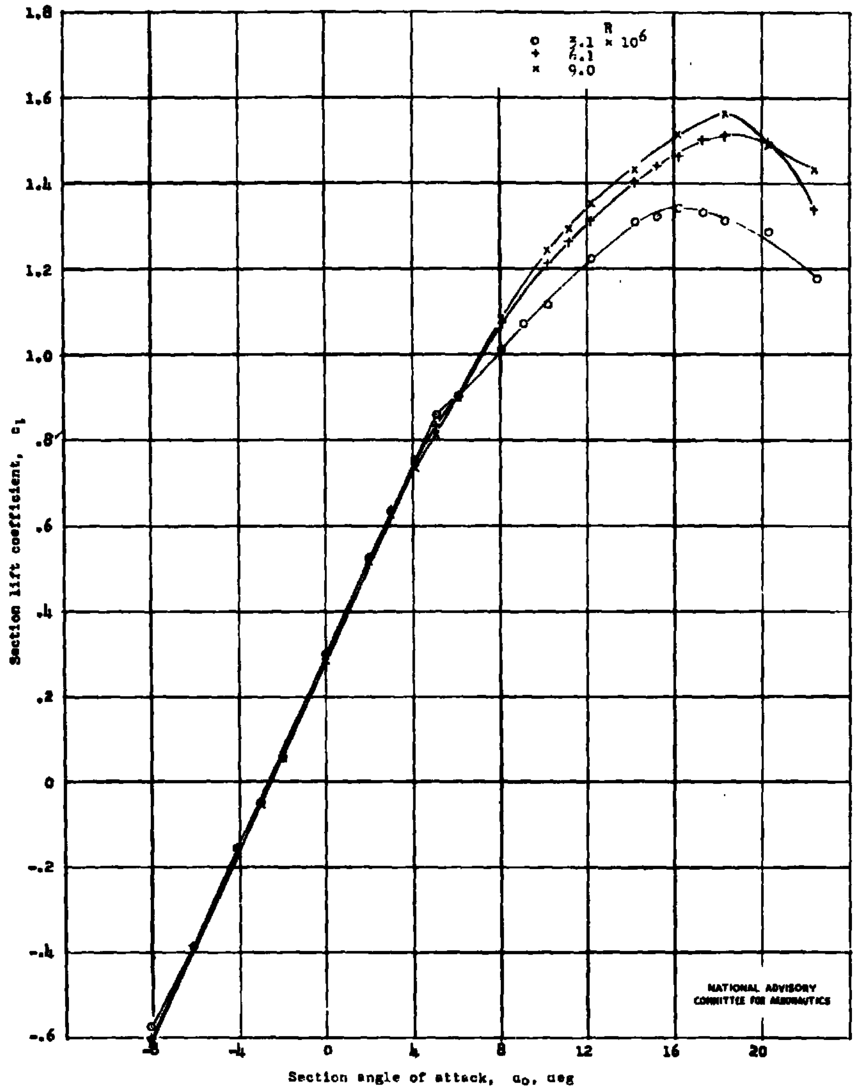

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Figure 2 .- (c) Model having 24-inch chord in TDT. Concluded.

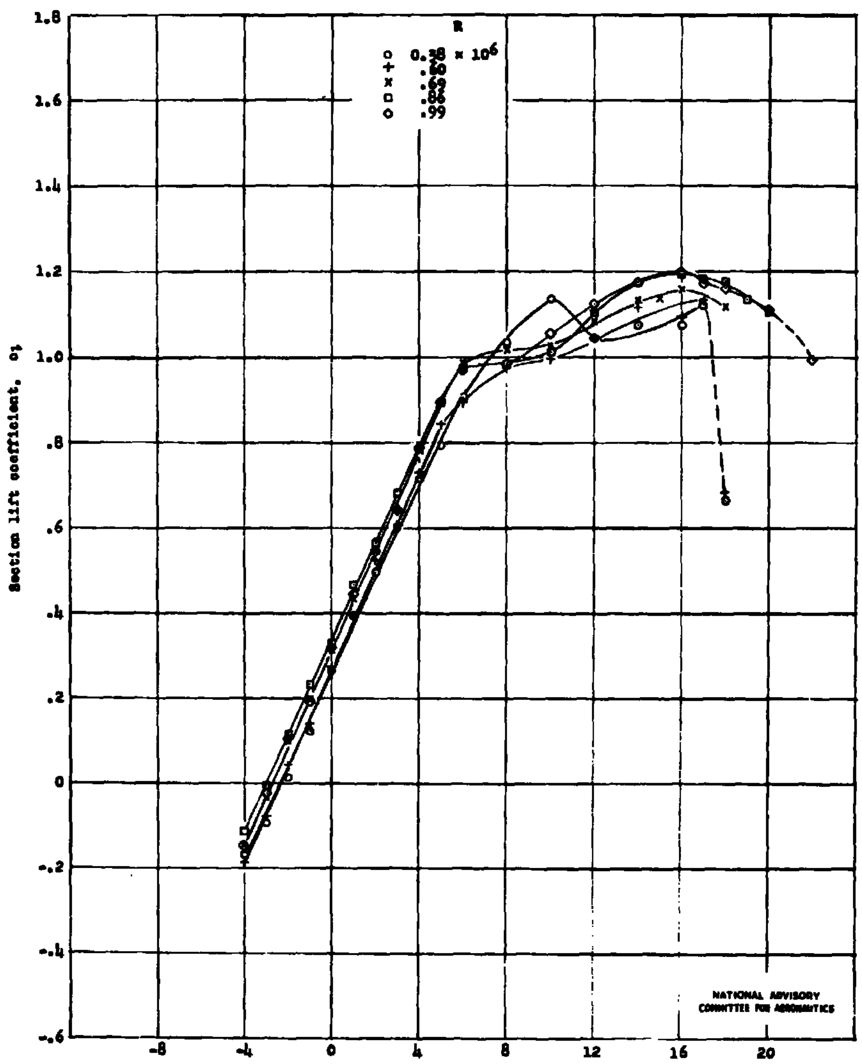

Figure 3.- Lift characteristics of the NACA 65_3-418 airfoil section; 6-inch-chord model in TDT.

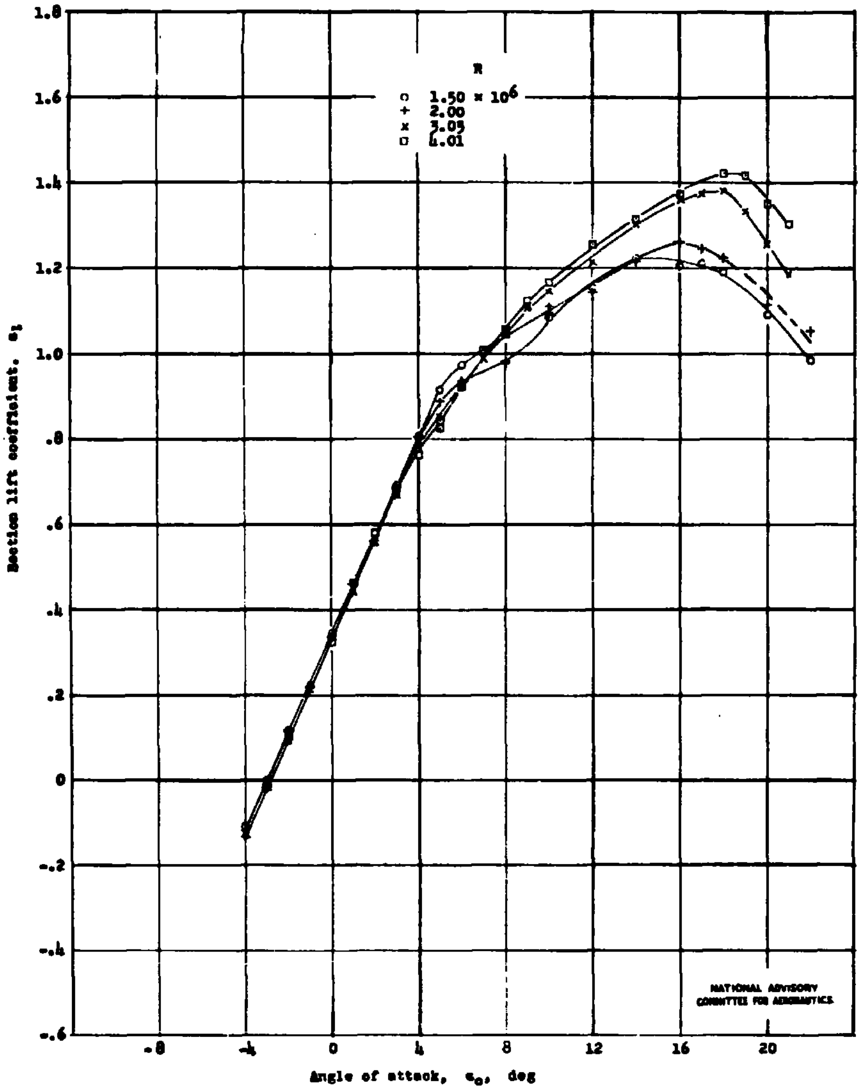

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Figure 3 .- Concluded.

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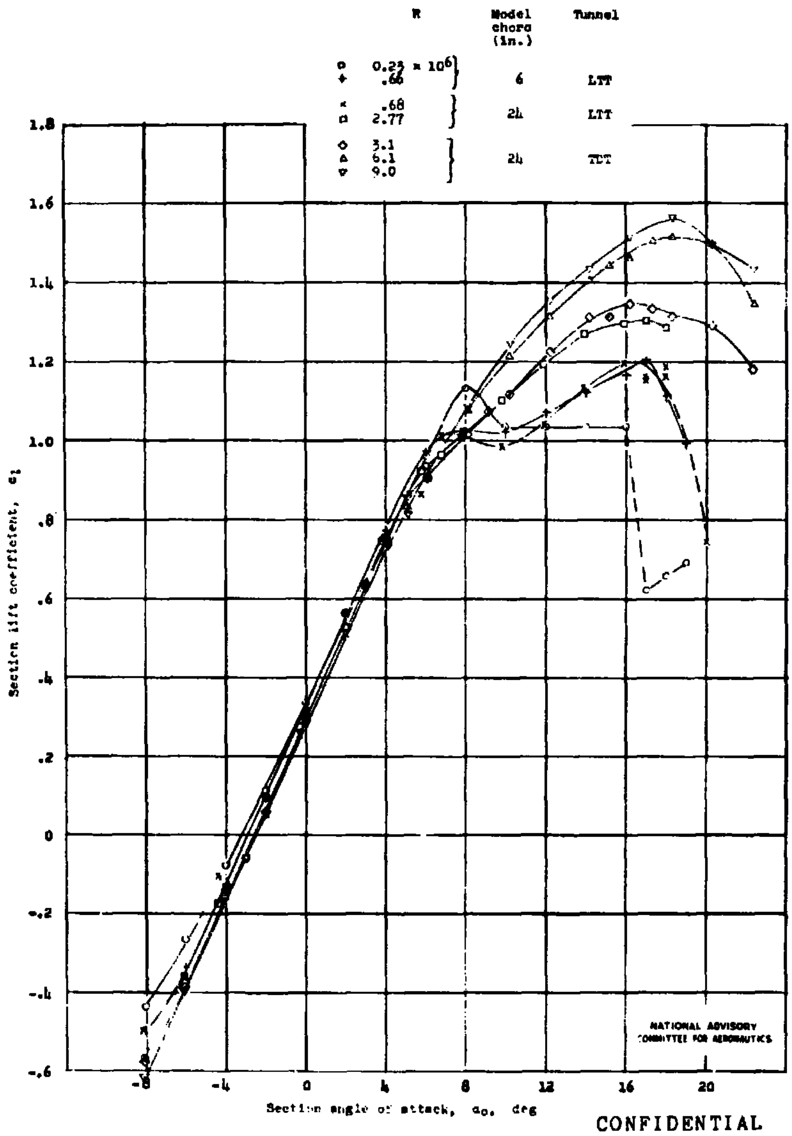

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Figure 4.- Lift characteristics of the NACA 65_3-418 airfoil section through the entire range of Reynolds numbers.

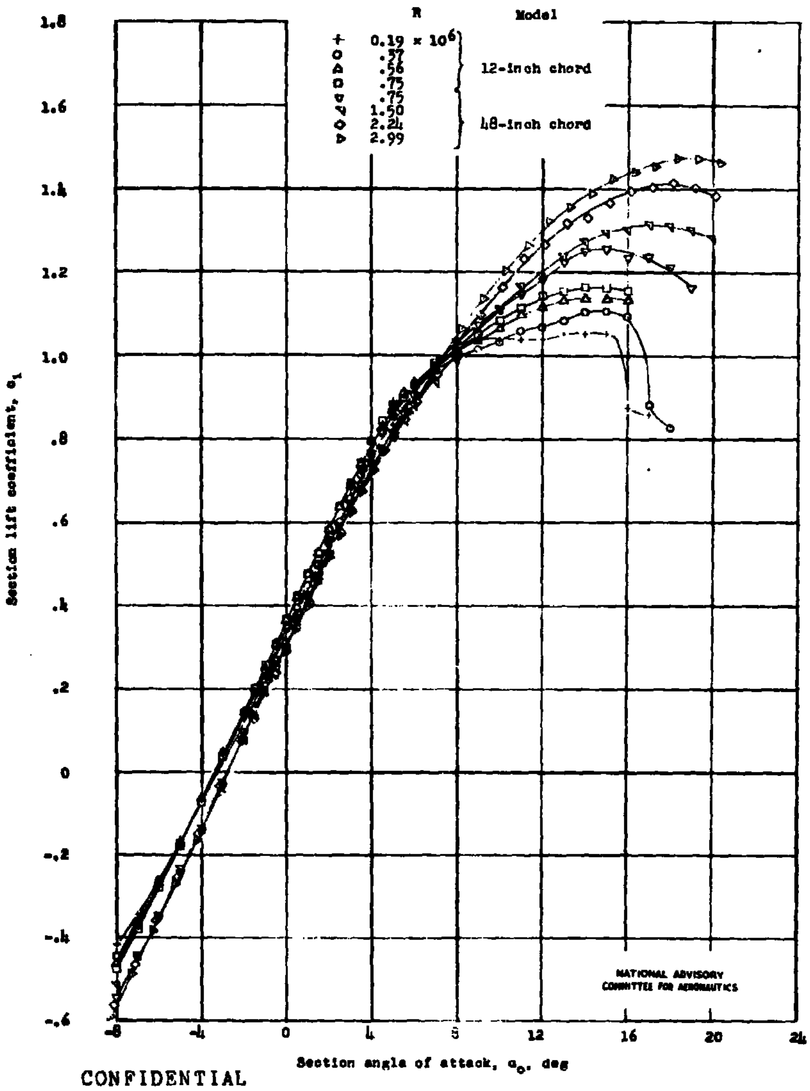

Figure 5.- Lift characteristics of the NACA 65_3-418 airfoil section in the LMAL 7- by 10-foot tunnel (designated 7 by 10 tunnel).

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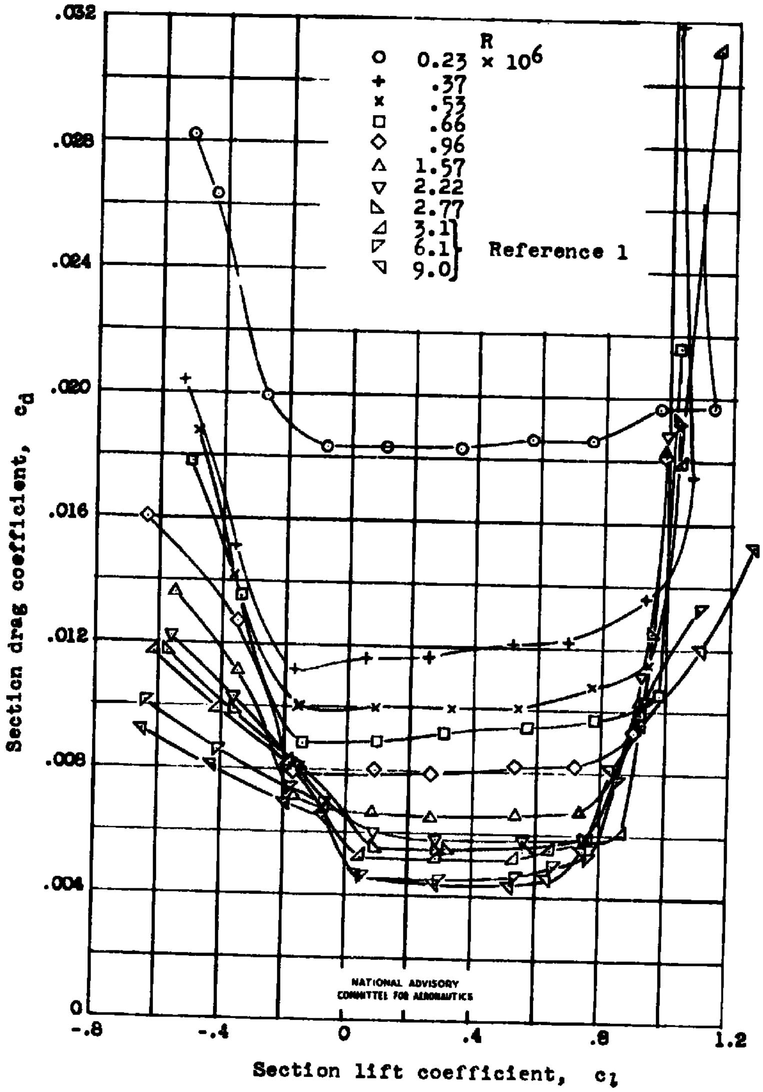

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Figure 6.- Drag characteristics of the NACA 65_3-418 airfoil section in the LTT and TDT.

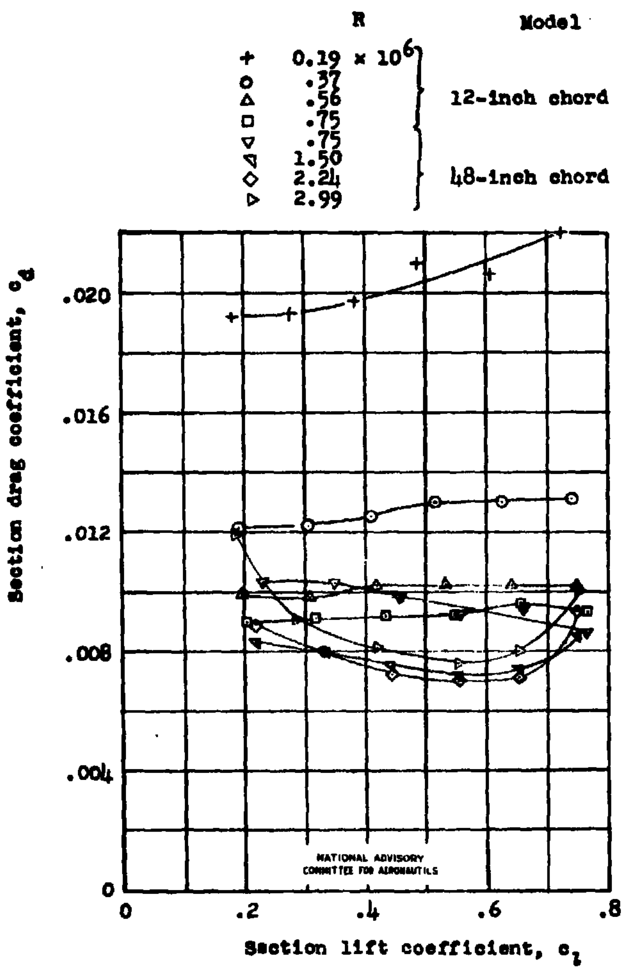

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Figure 7 .- Drag characteristics of the NACA 65_3-418 airfoil section in the 7 by 10 tunnel.

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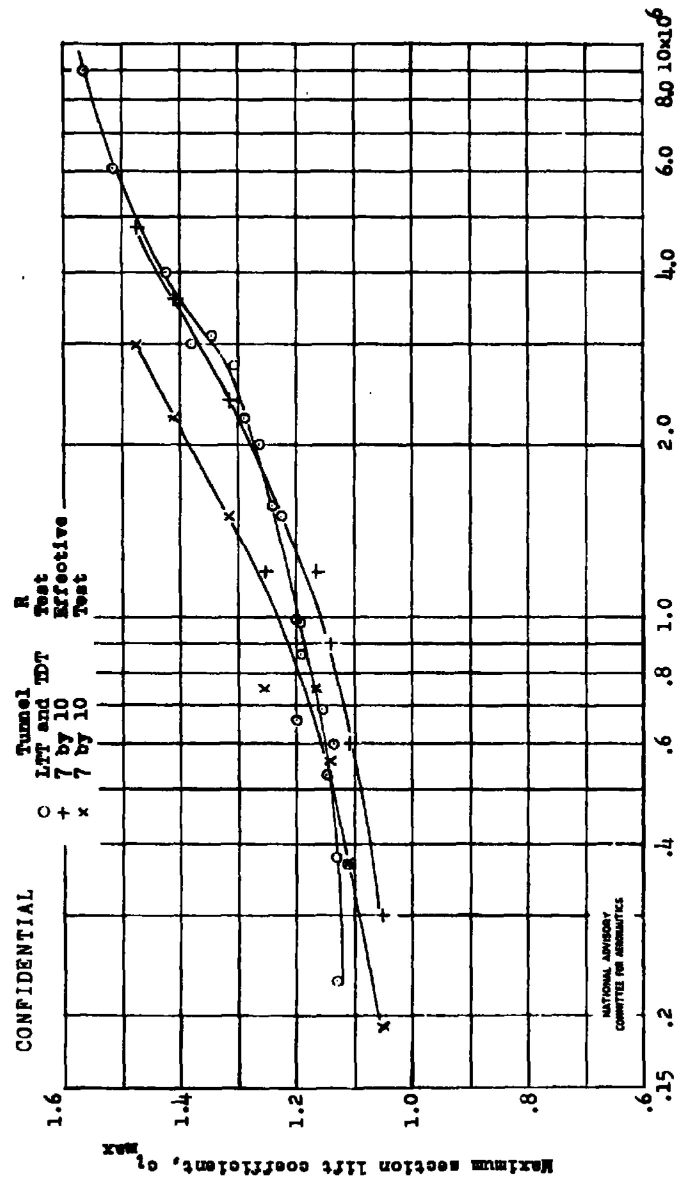

Reynolds number and effective Reynolds number

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Figure 8 .- Scale effect on maximum lift coefficient of the NACA 65_3-418 airfoil section.

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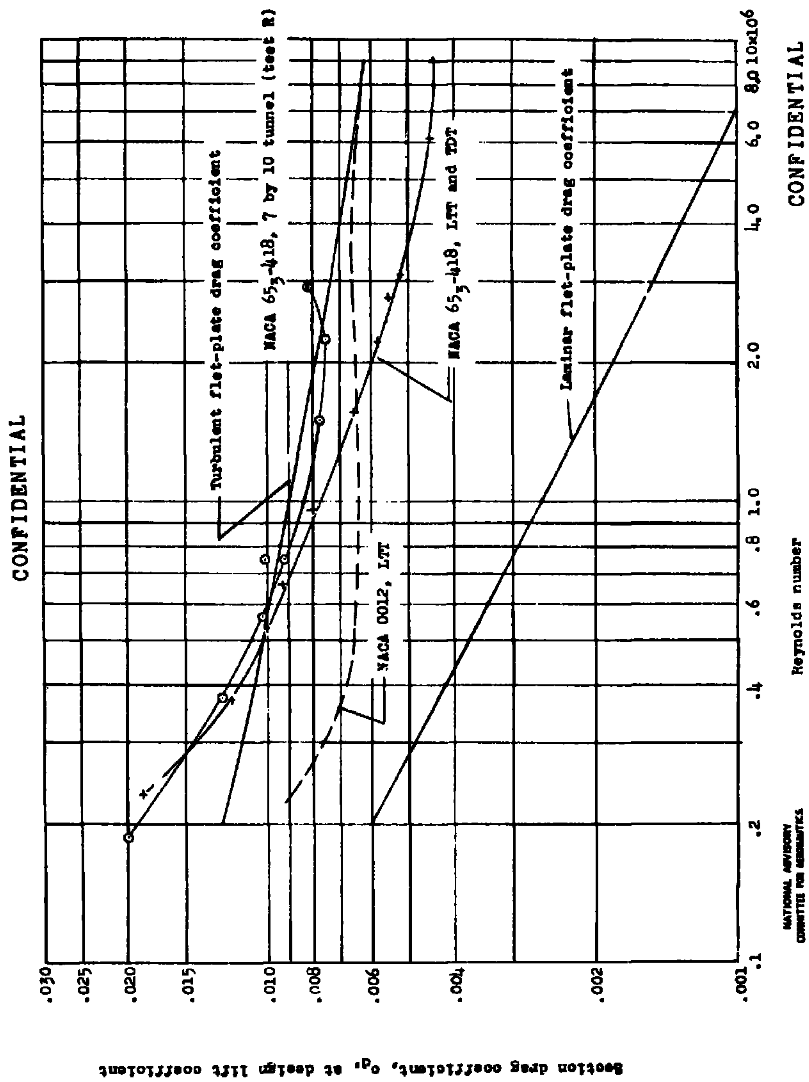

Figure 9.- Scale effect on drag coefficient at the design lift coefficient of the NACA 65_3-418 airfoil section.

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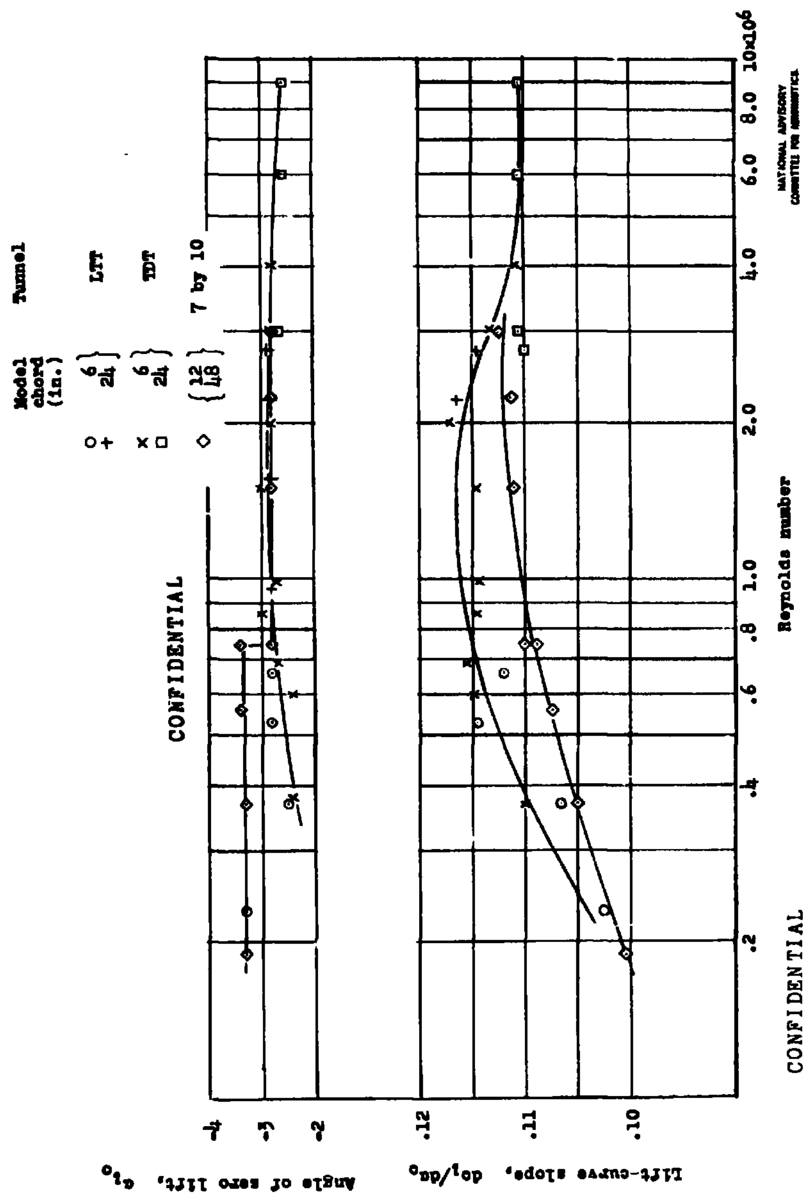

Figure 10.- Scale effect on lift-curve slope and angle of zero lift.

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Aerodynamic Characteristics

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DIVISION: Aerodynamics (2)

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